A Life Cycle Assessment for Reconstructed Soil

Authors: (TBC) Philomena Bacon, Amii Harwood, SC, MC, DCM, NW, Li Mao, Brian Reid.

Abstract

Despite its crucial role in supporting ecosystems, including food production and carbon sequestration, soil is frequently undervalued and in declining health. For example, in 2019 50 million tonnes of soil was sent to landfill in England, estimated to be in the region of 24.9 million tonnes CO_2 -eq. Whereas, diverting 1 tonne of material from inert landfill avoids 8.31kg CO_2 eq/t. In France 57% of construction waste ended up in landfill in 2019, with an estimated CO_2 -eq footprint of 1.9 million tonnes. Reuse of 'waste' materials offers opportunities to support vital soil functions, save money and recoup net environmental benefits. Aligned with EU ambitions to reduce material entering landfill and to embrace the circular economy, this research provides a first approximation to quantify reductions in CO_2 emissions that can be made by diverting surplus materials from construction and groundworks into soil fabrication. OpenLCA software, the Agribalyse v301.27052021 database and the ReCiPe 2016 Midpoint (H) impact model is used for the Life Cycle Assessment of reconstructed soil. Results show the net environmental benefits between 508-1145 kg CO2-eq/t of using reconstructed soils for *land reclamation*, *brownfield remediation* and *urban landscaping* in comparison to existing practices. Further by optimally locating licenced soil fabrication hubs, economies of scale can be achieved, transport distances reduced, testing and markets can be readily over seen by regulators offering stakeholders assurance of quality and supply. Finally, these recipes contribute to a circular economy mindset, they play a significant role in moving away from a single use throw away society*,* freeing up scare landfill, creating reuses for waste components and encouraging society to invest in conservation. Useful impact results are also presented for the practitioner to use in selecting soil components, mechanical handling equipment and transport.

Key words: LCA; soil; reconstructed soil; OpenLCA; Agribalyse; ReCiPe 2016; erosion; agriculture; construction; quarry sludge; excavated waste.

1. Introduction

Soil degradation is the physical, chemical and biological decline in soil quality. Where there is a loss of soil organic matter in agricultural soil, fertility and structure decline impacting on nutrients levels, biodiversity, and stored carbon. Soil forms slowly but erodes rapidly (USDA 2022) and soil degradation has led to pressures on global land use increasing the threat to food security, hastening deforestation and impacting climate change. Soil degradation is due to both anthropogenic activities and natural phenomena. Whilst agricultural soil is becoming degraded, non-agricultural soil and subsoils often containing valuable minerals, are excavated through groundworks/construction and mining activity and viewed as a waste disposal problem, often being sent to landfill or used to back fill old quarries.

Landfill sites are unpopular with the public for several reasons: their proximity to housing lowers property values (Hirshfeld, Vesilind et al. 1992); and the constant stream of heavily loaded lorries causes dust and noise pollution (Hirshfeld, Vesilind et al. 1992), (Finnveden 1999) and (Zhang 2019). However, landfill is a finite resource and now recognized to be a legacy of an outdated philosophy being superseded by the circular economy mindset. Recent EU Directives (EU 2018),(EU 2018) to curb waste are driving changes through the circular economy (EC 2015), (EC 2020), motivating collaborations between donors and receivers to reuse otherwise waste materials.

The reuse of subsoils traditionally destined for landfill meets three important principles: helps to reduce land degradation; creates an efficient use for other finite resources (subsoils); and helps to conserve habitats (through fewer landfill sites and land restoration). While mostly privately owned, at a strategic level, governments control the location and volume of sites, increasingly opting to curb availability through landfill regulation and taxes. (BRGM, Colombano et al. 2010) have put a figure on the cost of landfill disposal to the French economy of approximately 2.3 billion euros annually.

The concept of reconstructing soils from otherwise waste materials offers a potential solution to the problems of agricultural soil degradation, erosion, and landfill blocking. This process is not new, Schofield, Pettitt et al. (2019) claim that mineral and organic waste materials, derived from a range of activities, have the potential for reuse as components of manufactured soils. Reconstructed soil is usually layered on top of degraded soil, it is defined as having artificially created horizons: a technical zone at the bottom; a developmental zone; and a growth zone, on top. Reconstructed soil differs from reconstituted soil; reconstituted soil is achieved by adding mineral and organic matter, to the top layer, of partially degraded soil. Reconstituted soil is a solution to rescue soils on the path to degradation; whilst reconstructed soil is a replacement for completely degraded or missing soil. A key criterion for reconstructed/reconstituted soil is to act as a growing medium, such that it retains and cycles nutrients to support long-term plant growth without the need for significant fertilizer inputs, (Schofield, Pettitt et al. 2019). The Eden[1] project in Cornwall, England, is an example of a fully reconstructed soil, which has been operating as a growing medium for over twenty years. Long term examples of reconstituted soil, include the use of urban compost in field trials from as early as the Nineteen Nineties to improve soil moisture and crop growth on sandy soils in Saudi Arabia, (Sabrah, Magid et al. 1995). Another example from Yvelines in France, is the use of urban compost waste in a decade long experiment growing crops, (Chalhoub, Coquet et al. 2012).

Although, current regulations across the EU prohibit the general reuse of groundworks subsoil, river sediment and quarry sludge (fine clay particles suspended in water) in agriculture, motivation to increase reuse/reduce dumping has led to recent regulatory changes (EC 2020). These changes incorporate circular economy principles enabling movement of material off-site under specific conditions as set out in the legislation; essentially the material becomes a product if the receiving site can take responsibility for ensuring a match to local terrain and appropriate use. This 'waste recovery' legislation is still in the development phase with new guidance opening up opportunities for reuse in France (Legifrance 2022). A key feature of the guidance is to avoid material being classified as 'waste', by identifying suitable uses for it as early as possible in the life cycle process. Similar guidance in place in England has successfully empowered construction to recycle 88% of its waste by co-developing 'Soil Management Plans' (CLAIRE 2011) (CLAIRE 2014) as part of the overall on-site construction strategy, thereby identifying a re-use of top/subsoil and other wastes prior to excavation; thus, avoiding the wasteful shipment of materials to landfill.

Life Cycle Assessment (LCA) is an internationally recognised framework used by the scientific community, governments, industry, and others to measure environmental impacts of processes and products across many fields covering three areas of protection: Human Health; Natural Environment; and Natural Resources. It is governed by the ISO 14040:2006 and 14044:2006. It is a multi-step, multi-criteria iterative approach to systematically track the energy, resource, and environmental impacts (flows) of products/processes. It provides a means to quantify and compare relative environmental impacts and benefits of those flows for alternative courses of action (Bates, Fox-Lent et al. 2015). There is an opportunity to report impacts using more than fifteen environmental

[1] Uses reconstructed soil made from sand, clay, and composted bark/urban green waste to grow a wide range of plants native to the tropics and temperate regions of the world.

categories and chemical releases such as climate change, water/air quality, and impacts on soil. Despite, LCA being an active management tool for more than three decades, there are still substantial gaps in knowledge with many processes yet to be assessed.

Through exploration of three scenarios, this research will follow an internationally recognised LCA framework to measure CO2 fluxes associated with waste material processes, firstly destined as 'end-of-life' to landfill, and secondly as components of reconstructed soil recipes. The aim of this research is to demonstrate that ReCon Soil recipes have the potential to:

i) Reduce waste to landfill for excavated soils;
ii) Reduce environmental impacts by replacing existing practices;
iii) Reduce environmental impacts from transportation by reducing journeys and distances to local hubs versus landfill;
iv) Contribute to a circular economy mindset, moving away from a single use throw away society, by land reclamation, brownfield remediation and preservation of land through a reduction in landfill;
v) Raise levels of soil organic carbon (SOM).

This research is set out as follows: The recipes and scenarios are described in Sections 2 and 3. In Section 4 the LCA methodology is described and followed. Section 5 presents the environmental impacts results in the form of Global Warming Potential (GWP) CO2 equivalent fluxes for the recipes and scenarios. Section 6 concludes.

2. Reconstructed Soil recipes

Reconstructed soil recipes have been developed by the ReCon Soil project, some share basic components such as composted urban green waste and native topsoil. Table 1 summarises three recipes by weight. One has been developed in France, two in England; although all can be constructed in either location using locally available materials.

Recipe /component (tonnes)	**Fr8Ex**	**E1Bc**	**E2Bc**
Excavated waste	0.33		0.375
Green waste compost	0.03	0.17	0.12
Composted bark		0.16	
Composted road sweep			0.12
Sand		0.44	
Biochar		0.05	0.01
Lignite clay		0.18	
Native component	0.64		0.375
Fr= France; E= England			

Table 1. Breakdown of ReCon Soil recipes in tonnes (native component is the existing subsoil or topsoil).

Fr8Ex is a recipe for a soil amendment (reconstituted) relying on there being a native soil to improve, it is designed to improve soil structure to help retain nutrients. It is likely that this would be suitable for uses such as land reclamation and urban landscaping. Creating this soil reuse excavated waste components as inputs which can be spread or mixed on site over existing native soil without the need for ploughing or further mixing of the native soil. In an agricultural setting for example, a mechanical handling vehicle with a large bucket to lift and spread the mixture over the site would be recommended. Such an application might be over stubble during the autumn, to a depth of a 5-10cm (approximate to 750/1,500 tonnes per ha) ready for spring planting. The basic waste materials; urban green waste compost, excavated subsoil should ideally be sourced locally to reduce transport emissions. Compost can be produced either by industrial processing or outside via windrow. recipe the inputs reuse excavated waste (shown in the BAU on the lower left section of the figure). The urban green waste can be made from either an industrial process for from windrow.

E1Bc is a fully constructed soil, it relies on the availability of components that can be mixed in small batches on or off-site and used to completely replace lost soils. Urban green waste and bark chippings are usually composted in industrial facilities off-site to PAS 100 standard and imported. Sand, biochar and clay are obtained from commercial sources.

E2Bc is a fully constructed soil made in a soil hub, from bespoke local components. The mineral content is derived from biochar, the combination of topsoil, subsoil and a compost like output (CLO) derived from road sweep from agricultural areas. This component contain soil washed/blown from agricultural land, leaves and grains and is cleaned through composting in a windrow facility over 10 to 14 weeks. Although, it can only be used under licence it is included for reference purposes and can be replaced with standard compost if necessary. As with E1Bc compost from urban green waste can be created either on site or off-site.

The main difference between Fr8Ex and recipes E1Bc and E2Bc is that these are fully reconstructed soils which can be made on or off site. The recipes are focused on improving the carbon sequestration potential of the new soil by including substantially more organic material and biochar. For E1Bc commercially sourced components such as sand and clay add to the mineral content and improve structure, although these could technically be replaced by excavated subsoils if available. For E2Bc the reuse of a road sweep compost like output is currently unique to the locality, although as discussed this can be replaced by standard compost to obtain similar benefits as a replacement topsoil.

3. Soil scenarios

Three soil scenarios are considered: Scenario 1 (S1) is a land reclamation project. An example of land in this context is agricultural soil in a degrading state, suffering from a loss of nutrients or compaction, flooding or erosion. Erosion leads to damage to the soil structure affecting its resilience leading to water logging and further loss of silt and nutrients. The typical remedy for degrading agricultural soil is to apply organic or inorganic fertilizers. This course of action is only a temporary remedy as issues relating to nitrogen run-off and erosion persist and soil can never fully recover, eventually land is taken out of agricultural use (either temporarily or permanently). As part of the comparative LCA methodology (discussed in Section 4), it is necessary to define system boundaries for S1 both in its base state, this is known as the business as usual (BAU) case and in its reconstituted state (using a ReCon Soil recipe). The system boundaries are shown in Figure 2 and 3.

Scenario 2 (S2) is a generic brownfield site requiring remediation. This type of site is typically denuded of topsoil, either due to contamination, mining, quarrying or other natural or man-made excavation activity. Subsoil loss or contamination, potential compaction and the complete absence of topsoil prevents replanting and productive reuse of the land. Typical remedies are to back fill it and allow the area to re-wild itself taking 20-30 years, for larger former quarry/mining areas, these may be left to form a lake over the surface. If restoration is carried out, topsoil from agricultural sources may be imported in the final stages for cover and planting. The BAU for this is simply the removal of contaminated soils for off-site remediation and onward deposit in landfill. The BAU system boundary is shared with groundworks/construction in Figure 2.

Scenario 3 (S3) is an urban landscaping project. This type of site has typically experienced a loss of topsoil most likely due to its removal for excavation for groundworks or construction. Scenarios S2 and S3 consist of two phases, the initial site clearance phase and the final landscaping phase. Excavated waste is the unwanted output from construction and groundwork activities; tunnelling, pipe laying, and road building/maintenance. In some cases, the coarse fraction is separated in a mobile plant and commercialized as recycled aggregate. What is not reused for backfilling at the site is shipped off to inert landfill (or used for quarry backfilling). Groundworks and housing construction take place in urban areas, once completed there is often a need to import new soil for landscaping, gardens, embankments, verges etc., finished off with turfing. Soil used for landscaping is usually relocated from agricultural land this action leads to degradation of agricultural land; but this type of impact cannot be assessed using LCA tools. For housing construction, space constraints lead to soil being sent to landfill.

4. Methodology

4.1 Overview of Life Cycle Assessment (LCA)

LCA is a steady-state approach, that is, it provides a snapshot of environmental impacts at a single point in time. By evaluating each of the life cycle stages, shown in Figure 1, for a product or process, the impacts can be summed to obtain one impact value which covers the whole life cycle. LCA is an environmental accounting tool relying on many datasets collected under different circumstances under the auspices of the internationally agreed framework for LCA studies, the (ISO_14040: 2006), and (ISO_14044: 2006) guidelines. These help to ensure standardisation; however, the level of precision is accepted to be less than other types of accounting. Peer reviewed assessments and global expert collaborations, bring together environmental impact assessments across the life cycle of many products, as either cradle-to-gate or cradle-to-grave, into a single value and are deposited in the databases. Data held in electronic libraries (mostly restricted to licenced access) is being constantly updated as technology advances providing a platform for replicability and reference. Although, in an ideal world, an LCA would be measured as a bespoke operation, practicality dictates that some generic assessments are based on location or industry. This will mean that assessments relating to different locations conducted at different times can be different; it is up to the practitioner to select the most appropriate assessment for their circumstances/location closely matching the circumstances as far as possible. However, despite, LCA being an active management tool for more than three decades there are still substantial gaps in knowledge with many processes yet to be assessed. There is also an element of built-in redundancy to some assessments as technology advances. For these reasons LCA can only be a guide not an absolute.

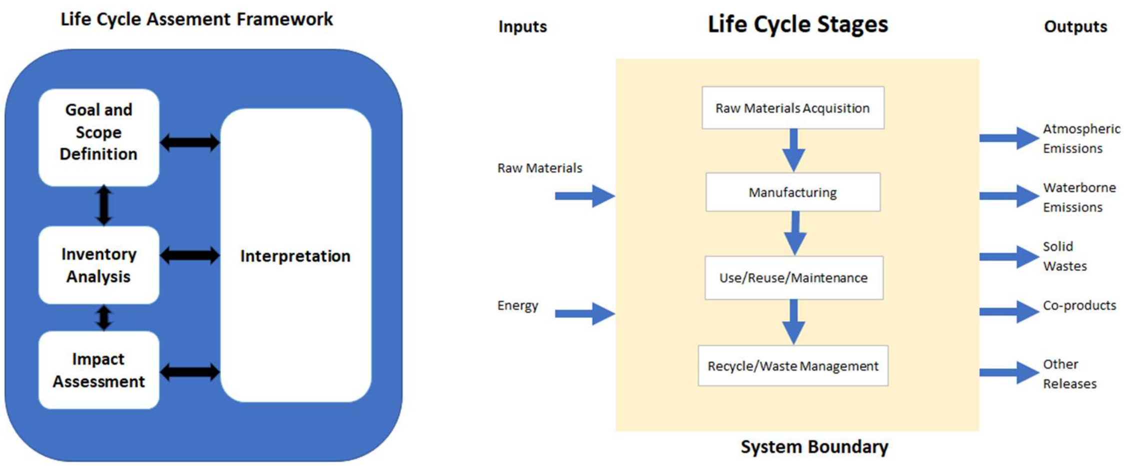

Figure 1. Overview of ISO LCA Framework (ISO 14040:2006) (left). Life Cycle Stages of an LCA (Matthews, Hendrickson et al. 2015)(right).

The free online 'OpenLCA' software (GreenDelta 2006) is used for the modelling in this assessment, using free open-source datasets: Argribalyse (including some ECOINVENT components) (ADEME 2022). This database has been selected as the main source for this analysis because it mostly closely matches the circumstances faced by ReCon Soil and it is available under an open licence. The climate model, ReCiPe 2016 Midpoint (H) (Huijbregts, Steinmann et al. 2017) is used to model the environmental impacts. ReCiPe 2016 measures global impacts over two horizons, midpoint (20-100 years) or end point (100-1000 years) with uncertainty rising over time. Midpoint was chosen as it contains more parameters, and the certainty level is slightly better. ReCiPe 2016 Midpoint (H) uses the Global Warming Potential (GWP) measure, which quantifies the integrated infrared radiative forcing increase of greenhouse gas expressed in kg CO_2-eq. For activities/process not available in the database, data from the literature and laboratory test results from the ReCon Soil project are used.

The LCA framework consists of four interactive phases as shown in Figure 1: goal and scope definition; inventory analysis; impact assessment; and interpretation of results. These stages will be described in the context of this study for the BAU scenarios and ReCon Soil recipes. In this way a standard approach is taken for comparative purposes. This comparative LCA (Matthews, Hendrickson et al. 2015)[2] is prepared to meet the requirements of the ReCon Soil project deliverable T1.3.

4.2 Goal and scope definition

The goal of this LCA is to quantify the carbon footprint (GWP kg CO_2-eq) of the process to construct the ReCon Soil recipes described in Section 2. These recipes mainly comprise of materials potentially diverted from otherwise waste facilities such as landfill. Soil and subsoils are not defined as having a carbon footprint (environmental impact) in life cycle assessments. This means that any changes in the way soil captures, or releases carbon cannot be tracked, the environmental impact being tracked is from transporting or handling it. The LCA process described here is therefore one of accounting for processes, transport, and measuring any benefits (negative impacts) derived from off-setting landfill emissions. The definition is a comparative assessment comparing ReCon Soil as a replacement for an existing business as usual (BAU) scenario. The basic scope is the construction and application of the recipe on site, covering the first two life cycle stages, as shown in Figure 1. Inputs are the raw

[2] Chapter 4.

materials and energy, standard outputs are atmospheric emissions (gases), waterborne and solid emissions. The technical term for this assessment is the 'cradle-to-gate' approach.

However, recall in Figure 1 the third stage shown is the 'use/reuse/maintenance' stage, this suggests a potential extension to the assessment. The 'use' stage of new products is especially difficult to quantify, due to unknowns such as performance, longevity, and opportunity costs, therefore LCA is normally conducted once a product has been in use for some time. Some 'use' stages of products are very short, such as single use plastics, and are therefore not a significant part of an assessment. Although, it is standard practice to extend life cycle assessments as far as possible to a 'cradle to grave' approach, this is normally done where LCA has the tools necessary to do so, and a clear idea of the lifespan of a product. In the case of ReCon Soil, a cradle-to-grave approach could extend to millions of years, LCA tools do not exist to enable this level of detailed assessment.

For ReCon Soil, for example, there is an expectation of a long-term legacy; that it will sequester more carbon (negative impact) than standard soils. However, LCA cannot currently quantify this type of data for soil, as a tool, it is designed to be standardised and systematically track the energy, resource, and environmental impacts (flows) of products/processes, since soil is not normally man-made some adaptations are made for the comparison.

For the interpretation of results it helpful to bear in mind that carbon dioxide releases although very important are not the only or best way to measure impacts. An important feature of ReCiPe 2016 Midpoint (H) is the extent of the impact assessment estimating impacts across a wide spectrum of releases, although not reported in the text these can be found in the Appendix.

4.3 Functional unit

Soil is a natural compound and is not recognised in LCA as having any impacts. Soil provides ecosystem services whilst part of a structure of soil horizons. Any outputs or values from soil are not fully understood without considering the application of the material to the (sub)soil and the processes occurring once it is incorporated. ReCon Soil recipes form manufactured soil-like output, but these can only become 'soils' once they are embedded into existing soil (soil amendments) or placed on top of existing soil horizons, as may be the case when used as replacement topsoil. For this reason, the cradle to gate system boundary at Figure 2, stops short of being a soil. For the purposes of this LCA the product system is the 'process' to produce 1 tonne of reconstructed soil; the function of the product is to reuse waste materials thereby avoiding landfill as a resource; the functional unit is 1 tonne of reconstructed soil as described by recipes detailed in Table 1 above.

4.4 System boundary

Defined in the ISO guidelines as 'all emissions and removals within the system boundary that have the potential to make a material contribution' (ISO_14040: 2006), and (ISO_14044: 2006). The life cycle stages of the system boundary are given in Figure 1.

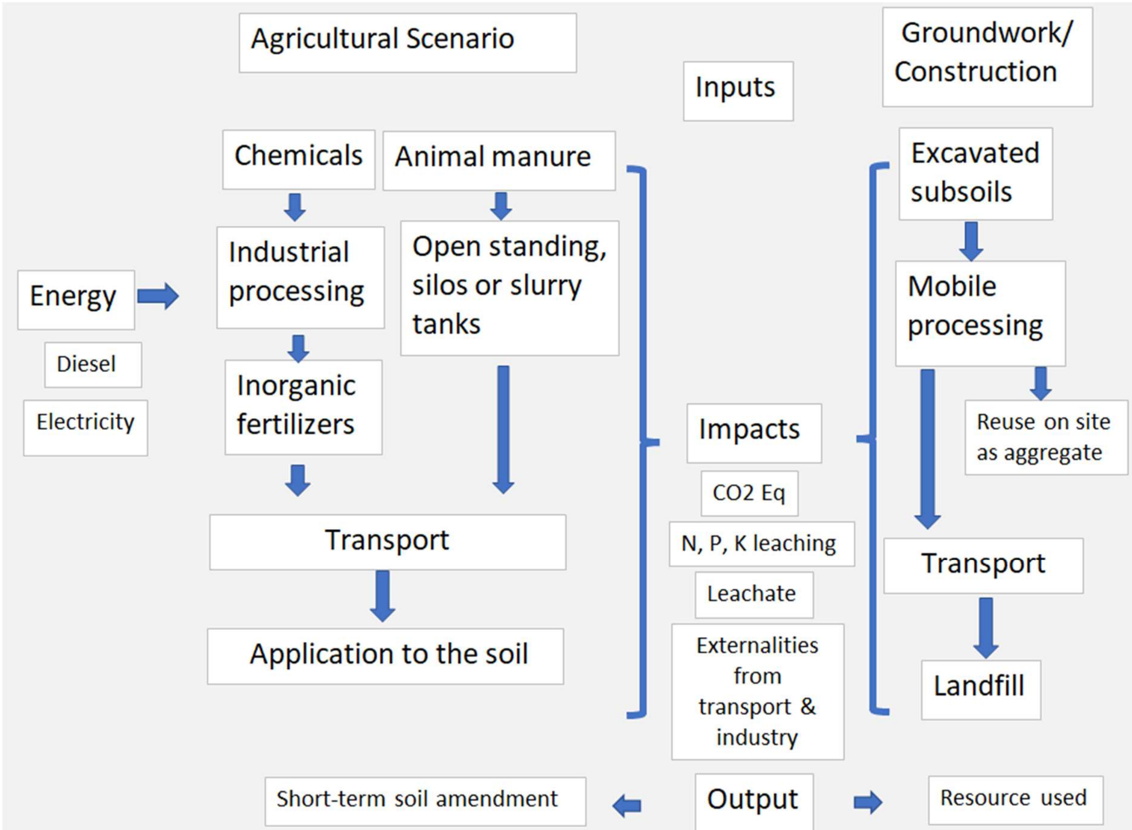

Figure 2. System Boundaries for BAU Scenarios for Agriculture and Groundworks/Construction

Figure 2 depicts the system boundaries for the BAU scenarios. The input energy is defined as electricity and vehicle fuel. The raw materials comprise of chemicals to process inorganic fertilizers and manure. The 'manufacturing stage' for agriculture is the activity of adding the processed inputs to the soil. As mentioned, soil is not regarded as having an environmental impact and in this case the output emissions are associated with the production of fertilizers rather than the leaching from the soil after they have been applied. The manufacturing stage for groundworks/construction is the re-processing of excavated waste in a mobile processor producing reusable aggregate and waste for landfill. The generic outputs are airborne emissions CO2 eq from transport and the industrial processes used to make the inputs, waterborne releases in the form of leachate and chemical run-off that are not assessed by LCA tools. The 'use' and end of life stages in each case is excluded.

Figure 3 depicts the system boundaries for the ReCon Soil recipes. The upper section shows the input materials listing the components from the recipes given in Table 1. The energy inputs are diesel for transport and the mobile aggregate processor and electricity for industrial composting and pyrolysis (for biochar production). The manufacturing stage is represented by the 'mixing' phase. The outputs are the same airborne and waterborne emissions as given in the BAU, whilst the solid emissions are the three ReCon Soils. The 'use' and end of life stages have been excluded due to a lack of data on projected performance of the recipes once applied to the soil.

For completeness both windrow and industrial composting have been included in these scenarios, these can be used interchangeably where applicable, however the environmental impacts of these two methods are very different. Industrial composting requires electrical energy to start the process, move and aerate the compost, autothermic heat produced by the system can reduce external energy inputs, or be exported. This leads to a reduction in airborne emissions, making the process more environmentally efficient than windrow.

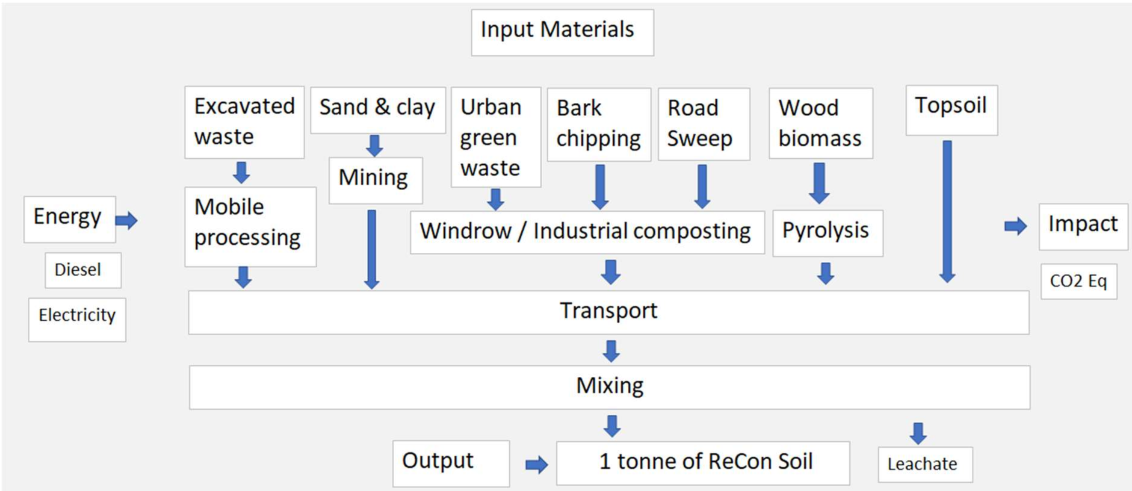

Figure 3. System boundary for ReCon Soil recipes

4.5 Inventory analysis

The attributional framework used in inventory analysis assumes that the total environmental burden of a process is shared amongst all the outputs. For example, the process associated with the removal of bark from a tree in a sawmill, will be apportioned across all products produced from the wood. Often the attributional method focuses on the economic value of the outputs (contribution to profit) or might be applied by volume or mass. What is important is to correctly recognise the value of waste from a process. As discussed, LCA is an iterative process assessed through all the LCA stages shown in Figure 1. At the bottom of the figure, there is the 'end of life (EOL) waste' stage, the cost of disposal of waste is assessed and then apportioned to the various products upstream, each taking a share of the burden according to some predetermined decision rule. Waste, therefore, has no independent environmental burden. However, once any waste is reused, it becomes a by-product capable of taking on a share of the environmental burden (Avadí 2020), effectively making other by-products more environmentally efficient. This accounting process can have a dramatic effect on comparisons.

	Activity	Inventory item	Units	Notes
Excavated roadside waste	Roadside regrading subsoils	Recycled aggregates (UK)	kg CO2 eq/t	Source: ERM 2010
	Transport to landfill	Transport, freight, lorry 16-32 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 6
	Landfill burden	Inert waste, for final disposal (RoW)	kg CO2 eq/t	Arigribalyse
BAU	**S1 Land reclamation**			
	Processing of cattle manure	Cattle manure, open solid storage	kg CO2 eq/t	Arigribalyse
	Transport for manure	Transport, freight, lorry 3.5-7.5 metric ton (GLO)	kg CO2 eq/t/km	Arigribalyse EURO 5
	Spreading manure	Fertilizing, solid manure or compost (charging and spreading), with frontal bucket and 5t spreader	kg CO2 eq/day	Arigribalyse
	Processing for inorganic fertilizers	Inorganic. average mineral fertilizer as N, from regional storehouse FR/U	kg CO2 eq/t	Arigribalyse
	Processing for inorganic fertilizers	Inorganic. average mineral fertilizer as KO2, from regional storehouse FR/U	kg CO2 eq/t	Arigribalyse
	Processing for inorganic fertilizers	Inorganic. average mineral fertilizer as P2O5, from regional storehouse FR/U	kg CO2 eq/t	Arigribalyse
	Transport for fertilizers	Transport, freight, lorry 7.5-16 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 5
	Spreading of fertilizers	Fertilising, by broadcaster	kg CO2 eq/ha	Arigribalyse
BAU	**S2 Brownfield remediation**			
	Site clearance of soil	Included in site processing		
	Transport to landfill of contaminated soil	Transport, freight, lorry 16-32 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 6
	Cleaning of contaminated waste via windrow	Compost of green waste	kg CO2 eq/t	Arigribalyse
	Landfill burden contaminated soil	Disposal, ordinary industrial waste, 22.9% water, to sanitary landfill	kg CO2 eq/t	Arigribalyse
	Transport for import of virgin topsoil	Transport, freight, lorry 16-32 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 6
BAU	**S3 Urban landscaping**			
	Removal of topsoil and subsoil	Included in site processing		
	Landfill burden	Inert waste, for final disposal (RoW)	kg CO2 eq/t	Arigribalyse
	Transport subsoil to landfill	Transport, freight, lorry 16-32 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 6
	Transport for topsoil export	Transport, freight, lorry 16-32 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 6
	Transport for virgin topsoil import	Transport, freight, lorry 16-32 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 6

Table 2. Inventory listing for BAU scenarios: excavated roadside waste; degrading agricultural land; urban landscaping.

The BAU cases in this analysis, describe some source materials as waste, the environmental burden of this in this context is therefore zero. By deploying waste in the ReCon Soil recipes and scenarios the environmental burden is no longer zero. To over come this paradox the displacement of waste to landfill is used to *represent* the environmental impact of waste. Environmental impact values for processing a tonne of material in sanitary or inert landfill are available in the Agribalyse V301-27052021 free database and used in this context as the representative impact source.

Tables 2 and 3 detail the inventories being evaluated for the BAU scenarios and ReCon Soil recipes. The descriptions (of flows) given accord with those found in the database or literature ((Sahoo 2021), (ERM 2010) (NSS&G 2021), the tables include the country of origin for where the assessment was undertaken, the source and the year. Corresponding results are presented in Section 5.

	Activity	Inventory item	Units	Notes
Fr8Ex				
ReCon Soil recipe	Roadside regrading of excavated waste	Recycled aggregates (UK)	kg CO2 eq/t/km	ERM 2010
	Transport for excavated waste	Transport, freight, lorry 16-32 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 6
	Processing compost- using windrow	Compost of green waste	kg CO2 eq/t	Arigribalyse
	Transport for compost	Transport, freight, lorry 3.5-7.5 metric ton (GLO)	kg CO2 eq/t/km	Arigribalyse EURO 5
	Native topsoil	In-situ	kg CO2 eq/t	
	Application of excavted waste to field	Fertilizing, solid manure or compost (charging and spreading), with frontal bucket and 5t spreader	kg CO2 eq/day	Arigribalyse
	Application of compost to field	Transport, tractor and trailer, agricultural | processing	kg CO2 eq/t/km	Arigribalyse
E1Bc				
ReCon Soil recipe	Composted bark/Industrial processing	Biowaste (ROW) treatment of biowaste industrial composting	kg CO2 eq/t	Arigribalyse
	Composted urban green waste/Industrial processing	Biowaste (ROW) treatment of biowaste industrial composting	kg CO2 eq/t	Arigribalyse
	Biochar production	Biochar emission burden of production (US)	kg CO2 eq/t	Sahoo 2021
	Sand extraction process	Sand extraction (US)	kg CO2 eq/t	NSS&G 2021
	Lignite clay extraction	Shredded ball clay (UK)	kg CO2 eq/t	Imerys 2022
	On site mixing using tractor	Transport, tractor and trailer, agricultural | processing	kg CO2 eq/t/km	Arigribalyse
	Transport for biochar	Transport, freight, lorry 7.5-16 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 5
	Transport for sand	Transport, freight, lorry 16-32 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 6
	Transport for clay	Transport, freight, lorry 16-32 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 6
E2Bc				
ReCon Soil recipe	Composted road sweep via windrow	Compost of green waste	kg CO2 eq/t	Arigribalyse
	Composted urban green waste via windrow	Compost of green waste	kg CO2 eq/t	Arigribalyse
	Biochar production	Biochar emission burden of production (US)	kg CO2 eq/t	Sahoo 2021
	Excavated waste	Ex housing site	kg CO2 eq/t	
	Site regrading of excavated waste	Recycled aggregates (UK)	kg CO2 eq/t/km	ERM 2010
	Native topsoil	Locally sourced	kg CO2 eq/t	
	On site mixing using tractor	Transport, tractor and trailer, agricultural | processing	kg CO2 eq/t/km	Arigribalyse
	Transport for subsoil	Transport, freight, lorry 16-32 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 6
	Transport for topsoil	Transport, freight, lorry 16-32 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 6
	Transport for biochar	Transport, freight, lorry 7.5-16 metric ton (RER)	kg CO2 eq/t/km	Arigribalyse EURO 5

Table 3. Inventory listing for ReCon Soil recipes Fr8Ex, E1Bc and E2Bc.

For completeness, the environmental impact associated with the task of sorting of excavated subsoils carried out at the roadside, is given specific consideration as part of the attributional methodology. This task usually performed using mobile aggregate sorting equipment captures re-usable gravel from the excavated waste, the remaining component consists of smaller grainsize subsoils that would otherwise be shipped to landfill. As discussed, the entire burden of processing waste would be associated with the original groundworks function. However, by repurposing this material as a soil amendment it is reasonable to assume that it can be reclassified as a by-product; able to take on a share of the environmental burden. Therefore, an allocation of 50% of the impact of recycling this material is included in the impact assessment for ReCon Soil.

5. Results: Impact assessment

Environmental impact results are presented in Table 4 for the BAU scenarios and Table 5 for the ReCon Soil recipes. The data corresponds to the inventory listing given in Tables 2 and 3. Data is arranged left to right in rows against the description of the activity. The value given in column 3 refers to a proportion in a recipe, for example, 0.1 for cattle manure is 100 kg, 0.2 for spreading manure is 1/5 of a day. The units and impact value stated in columns 4 and 5 correspond to the measurements listed in the database. Column 6 provides a row total of GWP in kg CO2-eq by multiplying the figures in columns 3 and 5. These are indicative results based on available data.

1	2	3	4	5	6	7
	Activity	**Amount**	**Units**	**Impact value**	**Row total kg CO2 -eq**	**Notes**
Excavated roadside waste	Roadside regrading subsoils	N/A	kg CO2 eq/t	N/A	N/A	Included in site processing
	Transport to landfill	Unknown	kg CO2 eq/t/km	0.161	Unknown	
	Landfill burden	1	kg CO2 eq/t	8.307	8.307	Inert landfill
BAU	**S1 Land reclamation**					
	Processing of cattle manure	0.1	kg CO2 eq/t	12.946	1.2946	
	Transport for manure	Unknown	kg CO2 eq/t/km	0.515	Unknown	
	Spreading manure	0.2	kg CO2 eq/day	449.16	89.832	
	Processing for inorganic fertilizers N	0.133	kg CO2 eq/t	1522.650	202.512	
	Processing for inorganic fertilizers KO2	0.133	kg CO2 eq/t	694.070	92.311	
	Processing for inorganic fertilizers P2O5	0.133	kg CO2 eq/t	982.020	130.609	
	Transport for fertilizers	Unknown	kg CO2 eq/t/km	0.212	Unknown	
	Spreading of fertilizers	1	kg CO2 eq/ha	23.31	23.31	
BAU	**S2 Brownfield remediation**					
	Site clearance of soil	N/A	t	N/A	N/A	Included in site processing
	Transport to landfill of contaminated soil	Unknown	kg CO2 eq/t/km	0.161	Unknown	
	Cleaning of contaminated waste via windrow	1	kg CO2 eq/t	679.39	679.39	
	Landfill burden contaminated soil	1	kg CO2 eq/t	497.47	497.47	Sanitary landfill
	Transport for import of virgin topsoil	Unknown	kg CO2 eq/t/km	0.161	Unknown	
BAU	**S3 Urban landscaping**					
	Removal of topsoil and subsoil	N/A	t	N/A	N/A	Included in site processing
	Landfill burden	1	kg CO2 eq/t	8.31	8.31	
	Transport subsoil to landfill	Unknown	kg CO2 eq/t/km	0.161	Unknown	
	Transport for topsoil export	Unknown	kg CO2 eq/t/km	0.161	Unknown	
	Transport for virgin topsoil import	Unknown	kg CO2 eq/t/km	0.161	Unknown	

Table 4. Environmental impact results for the BAU scenarios

As seen the distances for transport are unknown and are not calculated, technically distances are a separate entity unless specifically significant in the comparison. The impact values for transport kg CO2 eq/t/km can be used to estimate the potential burden, at the discretion of the practitioner. Summing the row total figures reported in Table 4 we arrive at a single footprint for each of the BAU scenarios: 539.87 kg CO2-eq/t for land reclamation; 1176.86 kg CO2-eq/t for brownfield remediation and 8.31 kg CO2-eq/t for urban landscaping excluding transport. Because soil has no impact the relocation of topsoil in the urban landscaping scenario cannot be estimated using LCA methodology this is represented by the landfill burden.

1	2	3	4	5	6	7
	Activity	**Amount**	**Units**	**Impact value**	**Row total kg CO2 -eq**	**Notes**
Fr8Ex						
ReCon Soil recipe	Roadside regrading of excavated waste	0.33	kg CO2 eq/t/km	1.85	0.61	At 50% burden
	Transport for excavated waste	Unknown	kg CO2 eq/t/km	0.161	Unknown	
	Processing compost- using windrow	0.03	kg CO2 eq/t	697.39	20.9217	
	Transport for compost	Unknown	kg CO2 eq/t/km	0.515	Unknown	
	Native topsoil	0.6	kg CO2 eq/t	N/A	N/A	In-situ
	Application of excavted waste to field	0.02	kg CO2 eq/day	449.16	8.9832	
	Application of compost to field	0.02	kg CO2 eq/ha	26.31	0.5262	
E1Bc						
ReCon Soil recipe	Composted bark/Industrial processing	0.16	kg CO2 eq/t	55.038	8.80608	
	Composted urban green waste/Industrial processing	0.17	kg CO2 eq/t	55.038	9.35646	
	Biochar production	0.05	kg CO2 eq/t	553	27.65	Sahoo 2021
	Sand extraction process	0.44	kg CO2 eq/t	5.5	2.42	
	Lignite clay extraction	0.18	kg CO2 eq/t	13	2.34	
	On site mixing using tractor	1.00	kg CO2 eq/t/km	0.35	0.35	
	Transport for biochar	Unknown	kg CO2 eq/t/km	0.212	Unknown	
	Transport for sand	Unknown	kg CO2 eq/t/km	0.161	Unknown	
	Transport for clay	Unknown	kg CO2 eq/t/km	0.161	Unknown	
E2Bc						
ReCon Soil recipe	Composted road sweep via windrow	0.12	kg CO2 eq/t	679.39	81.5268	
	Composted urban green waste via windrow	0.12	kg CO2 eq/t	679.39	81.5268	
	Biochar production	0.1	kg CO2 eq/t	553	55.3	Sahoo 2021
	Excavated waste	0.375	kg CO2 eq/t	N/A	N/A	Ex housing site
	Roadside regrading of excavated waste	0.38	kg CO2 eq/t/km	1.85	0.69	At 50% burden
	Native topsoil	0.375	kg CO2 eq/t	N/A	N/A	Locally sourced
	On site mixing using tractor	1.00	kg CO2 eq/t/km	0.35	0.35	
	Transport for subsoil	Unknown	kg CO2 eq/t/km	0.161	Unknown	
	Transport for topsoil	Unknown	kg CO2 eq/t/km	0.161	Unknown	
	Transport for biochar	Unknown	kg CO2 eq/t/km	0.212	Unknown	

Table 5. Environmental impact results for the ReCon Soil recipes.

The results for the ReCon Soil recipes are given in Table 5. Recall that Fr8Ex is a reconstituted soil, being an amendment to existing soil, and recall also that soil has no environmental impact. Following the deployment of ReCon Soil recipe FGr8Ex, for a reclaimed land scenario using 60% native soil, the estimated environmental impact is 31.04 kg CO2-eq/t, a reduction of 509 kg CO2-eq/t compared to the BAU land reclamation S1, excluding transport. Replacing windrow composting with industrial composting would reduce the environmental impact of this recipe by 19.08 kg CO2-eq/t. If this recipe was constructed off-site in a hub using 60% volume of a native topsoil, it could be used as a replacement soil for each of the other two scenarios: brownfield remediation and urban landscaping. The transport impact of bringing in the native soils would however be an important factor that would need to be included in the assessment, however notwithstanding that, the potential environmental impact reduction for S2 using Fr8Ex would be substantial at 1146 kg CO2-eq/t.

ReCon Soil recipes E1Bc and E2Bc are fully reconstructed soils, because E2Bc contains recovered native topsoil this feature extends its versatility to being either an amendment or a replacement soil. Each of these recipes is suited to being processed at a hub-site and transported without the need for further amendment. These contain small amounts of biochar, which was not available in the Agribalyse dataset. The production of biochar has many alternatives and source materials, which affect its average environmental impact, one (median) value amongst a range has been selected from the literature (Sahoo 2021). Similarly for the extraction of sand, there is no Agribalyse reference, and again there are a variety of ways to obtain and process sand, a single value has been selected from the literature (NSS&G 2021) alternative are found in (Xing, Tam et al. 2022) or extracted from aggregates found in (ERM 2010) and (Bascompta, Sanmiquel et al. 2022). The inclusion of these impact values from the literature is indicative only as the method employed to obtain the assessment may not be the same as the methods employed for the other materials, this adds uncertainty to the estimate, although every effort to avoid biasing the approach has been taken. Given these caveats the environmental impact of E1Bc is estimated to be 50.92 kg CO2-eq/t, this compares favourably with both BAU S1 and S2, returning a reduction in the environmental impact of 589kg CO2-eq/t and 1126 kg CO2-eq/t respectively, excluding transport. However, by replacing the industrial composting method with windrow would change the impact result, in this case it would increase by 209.83 kg CO2-eq/t

The environmental impact of E2Bc is estimated to be 219kg CO2-eq/t, this also compares favourably with both BAU S1 and S2, returning a reduction of 320 kg CO2-eq/t and respectively 957 kg CO2-eq/t excluding transport. Windrow composting has been used in this evaluation, if this was replaced with industrial composting for the green waste there would be a reduction in the overall impact of 76.3 kg CO2-eq/t. Note that no account has been taken for transport required to import native soil to the hub, although there would be an off-setting distance if this was potentially redeployed elsewhere.

It has not been possible to make a direct comparison with the recipes and the BAU for S3. Although, it is likely that there would be a benefit to using these recipes for urban landscaping, the fact that soil is not classified in LCA, is a barrier to making a fully informed assessment, the act of creating the recipes will have an environmental impact greater than the relatively small landfill impact recorded. If topsoil were being sent to landfill the impact would be 497.47 kg CO2-eq/t that could be avoided, however, there is no evidence to suggest that topsoil is being disposed of in landfill at this time. As discussed, the inert landfill burden has been included as a representative value.

Overall, the distances over which materials and waste are transported and the type of technology of vehicles will make a significant contribution to the viability of reusing waste material. The environmental impacts of the EURO 5 and EURO 6 trucks cited here is smaller than older models, although it is unlikely that all carriers are running the most efficient trucks. The impact values cited can be used as a guide for practitioners in any site level assessment.

6. Conclusions

Five aims of this research were set out in the introduction. The first, to reduce waste to landfill has unequivocally been proven possible. For the second, it is acknowledged that the BAU scenarios are loosely defined and subject to refinement or bespoke implementation, however, the indicative carbon flux results suggest that the ReCon Soil recipes have the potential to replace existing scenarios reducing the environmental impact on a like-for-like basis.

For the third aim- to reduce transportation- it was not possible to assess. The viability of the recipes and processes is heavily reliant on transport both for waste and for imported components, but there is no doubt that logistics could be managed to balance out these impacts. One solution to this is to set up optimally located licenced soil fabrication hubs. These would deliver economies of scale, enabling pick-up and drop-off, and reducing transport distances. Manufacturing in soil hubs offers an easy route for compliance testing, offering stakeholders assurances and providing confidence to users of quality and supply.

Setting aside the comparisons presented, it has been shown that reconstructing soil following the ReCon Soil recipes involves front-loaded impacts and some on site transport emissions. One might question the justification for making the effort to construct soil, given soil has no LCA impact or benefit. The answer to this is a philosophical one which links into the fourth aim, that these ReCon Soil, recipes can contribute to a circular economy mindset. It is evident that, these recipes have the potential to play a significant role in moving away from a single use throw away society for excavated waste, freeing up scare landfill, creating reuses for waste components and encouraging society to invest in conservation; things that cannot be directly measured but which will have a beneficial legacy.

Only one aim remains unproven- that ReCon Soil recipes can raise levels of soil organic carbon. The rationale behind this is that ReCon Soil recipes are chemically and biologically designed to provide the right conditions for further carbon sequestration over the medium to long term, over an above the performance of the existing natural soil. As discussed by (Avadí 2020), observations by (Vicente-Vicente, García-Ruiz et al. 2016), (Tuomisto, Hodge et al. 2012) and others show that organically-fertilised soils initially tend to contain higher levels of soil organic matter (SOM) than other mineral amended soils. However, there is no agreed method for measuring carbon sequestration in soils, one method is to measure the amount of biomass produced by the soil. Soils that have organic fertilization only, tend to perform less well in growing biomass over time, than soils with organic-mineral amendment, this is due to the chemical reaction of carbon mineralisation converting carbon to an available form for biomass uptake; over time therefore organic-mineral soils perform better (Schofield 2015). The ReCon Soil recipes have been developed with organic-mineralisation as a feature; with the addition of biochar or mineral rich excavated subsoils (Schofield, Pettitt et al. 2019). It is envisaged that laboratory testing of these soils will support the claim that ReCon Soils also sequester more SOM than other soils, however, as discussed, there is no formally recognised measurement of SOM in LCA.

For further interpretation of the results it is important to bear in mind that carbon dioxide releases although very important are not the only or best way to measure impacts. The benefit of using ReCiPe 2016 Midpoint (H) is the reporting of a range of emissions against several impact categories. These impacts are given in the Appendix.

Appendix

Impact categories	Database description from AGRIBALYSE v301.27052021 -->	Biowaste (RoW)| treatment of biowaste, industrial composting | Cut-off, S - Ecoinvent	Compost of green waste	Cattle manure, open solid storage	Inorganic. average mineral fertilizer as N, from regional storehouse FR/U	Inorganic. average mineral fertilizer as KO2, from regional storehouse FR/U	Inorganic. average mineral fertilizer as P2O5, from regional storehouse FR/U	Fertilizing, solid manure or compost (charging and spreading), with frontal bucket and 5t spreader	Electric fertilizing, solid manure or compost (charging and spreading), with frontal bucket and 5t spreader/FR U	Fertilising, by broadcaster (GLO)	Transport, tractor and trailer, agricultural processing Europe	Transport, freight, lorry 16-32 metric ton (RER) EURO 6	Transport, freight, lorry 7.5-16 metric ton (RER) EURO 5	Transport, freight, lorry 3.5-7.5 metric ton (GLO) EURO 5	Inert waste, for final disposal Europe	Disposal, ordinary industrial waste, 22.9% water, to sanitary landfill Europe
From ReCiPe 2016 Midpoint (H)	Reference unit	per tonne	per tonne	per tonne	per tonne	per tonne	per tonne	per day	per day	per ha	t/km	t/km	t/km	t/km	per tonne	per tonne
Agricultural land occupation - ALOP	m2a	8.88	451.63	0.001	70.73	66.48	50.26	2.68	7.35	1.45	0.06	0.001	0.002	0.006	0.31	0.53
Climate change - GWP100	kg CO2-Eq	55.04	679.39	10.503	1522.65	694.07	982.02	449.16	110.31	26.31	0.35	0.161	0.212	0.515	8.31	497.47
Fossil depletion - FDP	kg oil-Eq	7.33	46.09	0.009	681.79	198.43	436.37	156.35	29.38	8.30	0.08	0.059	0.075	0.175	4.95	4.99
Freshwater ecotoxicity - FETPinf	kg 1,4-DCB-Eq	0.06	0.27	0.000	3.63	3.07	3.37	0.37	1.01	0.04	0.001	0.000	0.000	0.000	0.01	2.34
Freshwater eutrophication - FEP	kg P-Eq	0.01	0.03	0.000	0.47	0.33	0.34	0.04	0.11	0.00	0.00	0.000	0.000	0.000	0.00	0.01
Human toxicity - HTPinf	kg 1,4-DCB-Eq	7.87	45.29	0.023	491.10	430.61	317.35	63.13	163.74	6.20	0.11	0.042	0.051	0.118	1.57	388.18
Ionising radiation - IRP_HE	kg U235-Eq	2.82	57.35	0.008	143.74	60.43	172.52	46.58	140.99	1.83	0.02	0.012	0.016	0.036	0.97	4.05
Marine ecotoxicity - METPinf	kg 1,4-DCB-Eq	0.07	0.41	0.000	4.42	4.02	3.02	0.64	1.40	0.06	0.00	0.001	0.001	0.001	0.02	1.86
Marine eutrophication - MEP	kg N-Eq	0.10	0.67	0.000	1.40	0.69	0.79	1.84	0.12	0.10	0.00	0.0001	0.0002	0.001	0.02	1.56
Metal depletion - MDP	kg Fe-Eq	2.29	26.65	0.014	110.17	112.52	50.57	30.70	64.95	2.48	0.05	0.006	0.009	0.027	0.37	0.68
Natural land transformation - NLTP	m2	0.01	0.09	0.000	0.59	0.23	0.52	0.16	0.03	0.01	0.00	0.0001	0.0001	0.0002	-0.04	-0.06
Ozone depletion - ODPinf	kg CFC-11-Eq	0.000	0.000	0.000	0.0002	0.0001	0.0001	0.0001	0.000	0.000	0.000	0.0000	0.0000	0.0000	0.000	0.000
Particulate matter formation - PMFP	kg PM10-Eq	0.28	0.71	0.0001	2.50	1.36	2.58	1.76	0.30	0.10	0.00	0.0002	0.0003	0.001	0.03	0.04
Photochemical oxidant formation - POFP	kg NMVOC	0.12	2.04	0.002	4.06	2.18	2.76	5.43	0.62	0.31	0.00	0.0004	0.001	0.002	0.08	0.30
Terrestrial acidification - TAP100	kg SO2-Eq	1.82	1.25	0.0003	7.62	4.03	9.56	3.38	0.62	0.20	0.00	0.0004	0.001	0.002	0.05	0.10
Terrestrial ecotoxicity - TETPinf	kg 1,4-DCB-Eq	0.002	0.02	0.000	0.36	0.07	0.69	0.03	0.05	0.00	0.00	0.0001	0.000	0.000	0.002	0.01
Urban land occupation - ULOP	m2a	0.74	6.97	0.070	68.65	62.82	247.75	1.29	2.03	0.34	0.01	0.009	0.009	0.018	1.23	4.19

Table 2. Impact results from Agribalyse using ReCiPe 2016 Midpoint (H) (Feb 2023)

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